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R. M.A. Azzam

University of New Orleans, razzam@uno.edu

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The modulated reflected and nonreflected light fluxes, measured as the azimuth of incident linearly polarized light is varied, yield the absolute reflectances R_p and R_s of a dielectric or semiconductor surface. Application to a reflective Si detector determines the refractive index and thickness of a SiO_2 film on the detector surface.

Reflectance techniques have broad application to the determination of the optical properties of materials.[1–3] However, accurate reflectometric measurements are difficult and usually require double-beam methods. Normal-incidence reflectance also requires a Kramers–Kronig analysis[4] with attendant additional errors caused by extrapolation into experimentally inaccessible spectral regions. For these reasons, and because of the emergence of spectroscopic ellipsometry,[5,6] reflectance methods may be falling out of favor.

One attractive exception is measurement of the intensity reflectances R_p and R_s at oblique incidence. From R_p and R_s one can solve analytically (and noniteratively) for the real and imaginary parts of the complex refractive index of a bare substrate on a wavelength-by-wavelength basis.[7,8] In this paper a simple technique is described with which R_p and R_s are determined accurately and simultaneously without recourse to a separate measurement of the incident light flux. The technique is based on measurement of the temporal modulation depth (analogous to fringe visibility) of the reflected and nonreflected light fluxes when the incident light is linearly polarized and its azimuth is modulated by a suitable means. The method is nonellipsometric in that it does not involve analysis of the state of polarization of the reflected light. It is particularly applicable to semiconductor detector surfaces because the nonreflected light flux generates an electrical output signal whose modulation is determined directly. This is illustrated by an example in which R_p and R_s of a Si detector surface are measured and are used to determine the refractive index and thickness of a dielectric (oxide)-layer coating. The method is equally applicable to an all-dielectric system in which the refracted beam is received by a separate detector. The current study extends a previous rotating-polarizer technique for measuring R_p/R_s only from the modulated reflected light flux.[9]

Figure 1 shows the scheme for measuring R_p and R_s of a reflecting surface S at an angle of incidence ϕ. The nonreflected light generates an electrical signal i_1, using an integral or a separate photodetector. The latter case is that of a dielectric substrate, preferably in the form of a hemisphere or hemicylinder, through which the refracted light is transmitted to an isolated detector D_1 without diattenuation (Fig. 2). (For bulk absorbing media the photoacoustic effect[10] may be used to generate the first electrical signal i_1.) The reflected light is intercepted by another head-on photodetector D_2, which generates the second electrical signal i_2. The incident light is linearly polarized with a variable azimuth P measured from the direction p parallel to the plane of incidence. With linear photodetection it can be readily verified[9,11] that the received signals are modulated as follows:

$$i_k = i_{0k}(1 + m_{Lk} \cos 2P), \qquad k = 1, 2, \tag{1}$$

where i_0 is the average signal level and m_L is the modulation depth (or ac/dc signal ratio),

$$m_L = (i_{\max} - i_{\min})/(i_{\max} + i_{\min}), \tag{2}$$

where $i_{\max}$ and $i_{\min}$ are the extrema of the signal at $P = 0$ and 90°. In terms of R_p and R_s the modulation depths of the two detected signals are given by

$$m_{L1} = (R_s - R_p)/(2 - R_s - R_p), \tag{3}$$

$$m_{L2} = (R_p - R_s)/(R_p + R_s). \tag{4}$$

The author is with the Department of Electrical Engineering, University of New Orleans, New Orleans, Louisiana 70148.

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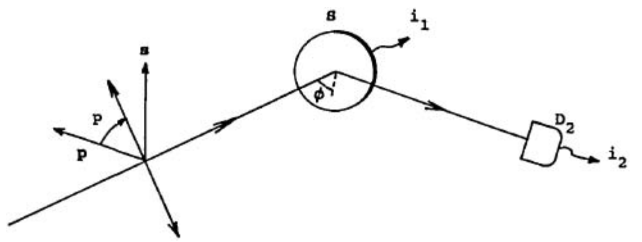

Fig. 1. Scheme for measuring the absolute reflectances of a surface S for p- and s-polarized light at an angle of incidence ϕ. The incident light is linearly polarized at a variable azimuth P; i_1 and i_2 are electrical signals generated by the nonreflected and reflected components of the incident radiation with linear photodetectors D_1 (integral with the sample, not shown) and D_2.

Equations (3) and (4) can be solved for R_p and R_s to obtain

$$R_p = m_{L1}(1 + m_{L2})/(m_{L1} - m_{L2}), \tag{5}$$

$$R_s = m_{L1}(1 - m_{L2})/(m_{L1} - m_{L2}). \tag{6}$$

Equations (5) and (6) provide the basis for the measurement of the absolute reflectances for the p and s polarizations without recourse to conventional reflectometry. By digital Fourier analysis of the two received signals i_1 and i_2, m_{L1} and m_{L2} and hence R_p and R_s are determined accurately.

The brute-force technique for azimuth modulation is mechanical rotation of a quality (achromatic, crystal) linear polarizer as is common in rotating-polarizer ellipsometry.[12] This simple but relatively slow approach lends itself well to reflectance to spectroscopy. It requires that the light source be unpolarized or partially or totally circularly polarized. To avoid the problem of residual linear polarization of the source, a fixed polarizer followed by a rotating polarizer may be used. In this case the signals should be normalized by an intensity modulation factor equal to the squared cosine of the azimuth difference between the two polarizers. Faster but less spectroscopic schemes for polarization modulation are the following: (1) A fixed polarizer with its transmission axis at $P = 0$ followed by an electro-optic linear retarder with its fast axis azimuth at 45°. The retarder is subjected to a square-wave voltage that alternates between 0 and the half-wave voltage to produce binary polarization modulation of the incident light between the p and s states. (2) A fixed polarizer at 45° azimuth followed by an ac-driven Faraday cell that produces sinusoidal rotation of 45° amplitude to sweep the incident linear polarization azimuth between 0° and 90°. In this case the signal wave forms are more complicated but digital Fourier analysis is still applicable.[13] (3) Use of the rotating linearly polarized source of Shamir and Fainman.[14]

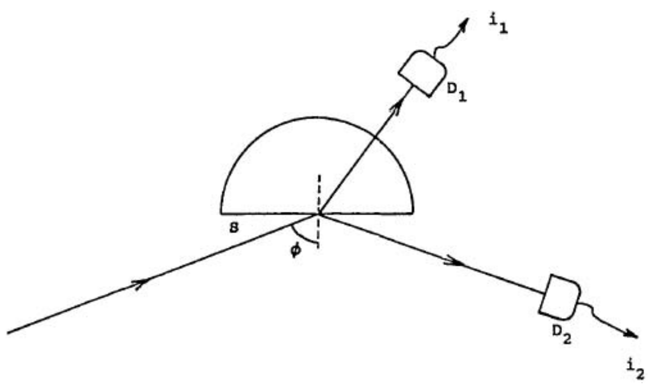

Fig. 2. Dielectric hemicylindrical or hemispherical samples suitable for applying the technique of Fig. 1 with a separate first detector D_1.

As an example we took measurements at 70° angle of incidence on the front surface of a 2.5-cm-diameter reflective, windowless, Si p-i-n photodiode using a circularly polarized 633-nm He–Ne laser and a rotating Glan-Thompson polarizer. A (small-area) conventional Si photodiode was used as the second photodetector. The outputs of the two detectors were sampled at 5° angular positions of the rotating polarizer, and a least-squares fit of the data to Eq. (1) yielded $m_{L1} = 0.2168$ and $m_{L2} = 0.4336$. From Eqs. (5) and (6) one obtains $R_p = 0.1888$ and $R_s = 0.4778$.

The test surface of the first Si photodiode was known to have a SiO_2 film with a nominal half-wave thickness at normal incidence (as specified to and delivered by the vendor). With $\lambda = 633$ nm and an assumed refractive index $n = 1.46$ for the oxide film, the estimated oxide-film thickness was $d = (\lambda/2n) = 217$ nm. From the equations of light reflection by a

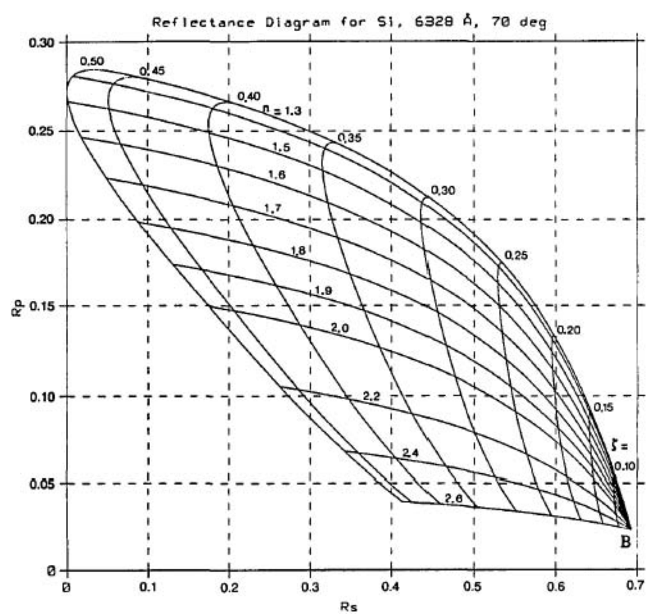

Fig. 3. Nomogram for relating the measured polarized-light reflectances R_p and R_s of a Si surface coated with a dielectric thin film to the refractive index n and normalized thickness ζ of the film. These data are for a 70° angle of incidence and 633-nm wavelength. The complex refractive index of Si at 633 nm is taken as 3.85–j0.02. Point B represents the bare Si substrate. The constant-ζ curves for $\zeta > 0.5$ coincide with the corresponding ones at $1 - \zeta$.

film–substrate system,[15] $n = 1.46$ and $d = 217$ nm as starting values, and the measured reflectances $R_p = 0.1888$ and $R_s = 0.4778$ at $\phi = 70°$, a two-dimensional Newton–Raphson method yielded $n = 1.457$ and $d = 204.3$ nm as the true refractive index and thickness of the oxide film. The complex refractive index of the Si substrate at 633 nm was taken[16] to be $3.85\text{–}j0.02$. The same technique can be used to characterize other dielectric coatings on Si. Figure 3 shows a useful nomogram that relates R_p and R_s at $\phi = 70°$ to the coating refractive index n and normalized thickness $\zeta = d/D_\phi$, where $D_\phi = (\lambda/2)\,(n^2 - \sin^2\phi)^{-1/2}$ is the film-thickness period. Similar nomograms for this or other material systems at any angle of incidence can be generated.

In summary, a novel method is described for measuring the absolute reflectances of a surface for the p- and s-polarized light at oblique incidence. The technique uses polarization (azimuth)-modulated incident light and involves the detection of two signals generated by the reflected and nonreflected light fluxes. It is readily applicable to semiconductor detector surfaces and also to dielectric (coated or uncoated) substrates. As a simple example, one applies the method to determine the refractive index and thickness of an oxide layer on a windowless Si photodiode.

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